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## New class of magnetoresistance oscillations: interaction of a two-dimensional electron gas with leaky interface phonons

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**Abstract.** We report on a new class of magnetoresistance oscillations observed in a high-mobility two-dimensional electron gas (2DEG) in GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures. Appearing in a weak magnetic field ( $B < 0.3$  T) and only in a narrow temperature range ( $2 \text{ K} < T < 9 \text{ K}$ ), these oscillations are periodic in  $1/B$  with a frequency proportional to the electron Fermi wave vector,  $k_F$ . We interpret the effect as a magnetophonon resonance of the 2DEG with thermally excited leaky interface-acoustic phonons. Calculations show a few branches of such modes existing on the GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As interface, and their velocities are in quantitative agreement with the observation. We show that electrons mostly interact with the phonons carrying a wave vector  $q = 2k_F$ .

There are several classes of transverse magnetoresistance (MR) oscillations known to exist in a two-dimensional homogeneous electron gas (2DEG). The most common of these are the Shubnikov–de Haas oscillations (SdH), which arise from a magnetic field  $B$ -induced modulation of the density of states at the Fermi level  $E_F$ . They become more pronounced with decreasing temperature  $T$ . The magnetophonon resonance (MPR) [1, 2] is a source of another class of oscillations resulting from the absorption of bulk longitudinal optical phonons. These resonances appear under the condition  $\omega_{LO} = l\omega_c$ , where  $\omega_{LO}$  and  $\omega_c = eB/mc$  are the optical phonon and cyclotron frequencies respectively,  $l$  is an integer, and  $m$  is the effective mass of the carriers. These oscillations are only seen at relatively high  $T \sim 100\text{--}180 \text{ K}$  [2]. Both SdH and MPR are periodic in  $1/B$ , but the SdH frequency (reciprocal period) scales with electron density as  $n_e$ , whereas MPR is  $n_e$ -independent.

In this paper, we report on a new class of MR oscillations observed in a high-mobility 2DEG in GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures. Unrelated to either of the above origins, these novel oscillations are still periodic in  $1/B$ , but they appear *only* in a narrow temperature range ( $2 \text{ K} < T < 9 \text{ K}$ ), and their frequency scales with  $\sqrt{n_e}$ . We interpret the data in terms of a magnetophonon resonance mediated by thermally excited *leaky interface-acoustic phonon* (LIP) modes. In principle, the surface modes might provide a good explanation as well, but in our case 2DEG is located so far from the surface ( $\sim 0.5 \mu\text{m}$ ) that no such interaction is possible.

The leaky interface modes have been studied for a few decades in connection with the Earth's crust [3]. The term “leaky” shows that the waves propagate at a small angle with the interface, so that the energy radiates towards the outside media. At some specific parameters these waves may not be leaky [4], but for the interface under study all of them are leaky. Despite the fact that LIP is commonly presented in layered material systems [5], it has so far not been considered on the GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As interface. Due to radiation of energy, the frequency and velocity of leaky waves are complex:  $u = \omega/q = u_R - iu_I$  with  $u_I \ll u_R$ .

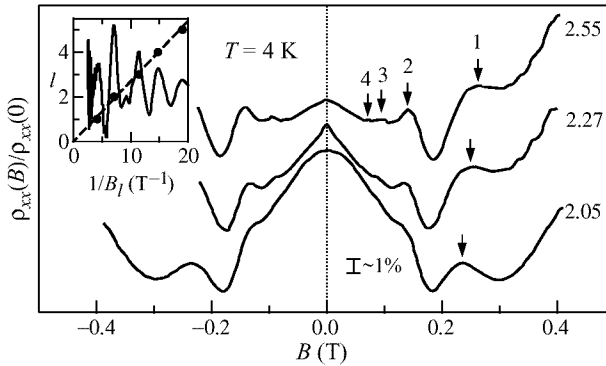
The novel oscillations can be explained by a simple momentum selection rule which is derived later in the paper. It says that at high Landau levels (LLs) the electrons interact predominantly with the interface phonons carrying a wave vector  $q = 2k_F$ , where  $k_F$  is the Fermi wave vector of the 2DEG at zero  $B$  field. The condition for resonant absorption or emission of an interface phonon is then given by

$$2k_F u_R = l\omega_c, \quad l = 1, 2, 3, \dots \quad (1)$$

We claim that Eq. (1) determines the values of  $B$  for the *maxima* in these new MR oscillations. It shows that the oscillations are periodic in  $1/B$  with a frequency  $f = 2k_F u_R / e$ . Evidently, the bulk phonons can not account for the resonance, since their frequency depends on  $q_z$ , while the selection rule includes lateral momentum only.

Our primary samples are lithographically defined Hall bars cleaved from modulation-doped GaAs-Al<sub>0.3</sub>Ga<sub>0.7</sub>As heterostructures of high-mobility  $\mu \approx 3 \times 10^6$  cm<sup>2</sup>/Vs. The wafers are grown by MBE on the (001) GaAs substrate. At low  $T$ , the density of the 2DEG,  $n_e$  (in units of  $10^{11}$  cm<sup>-2</sup> throughout the text), can be tuned by a combination of LED illumination and the NiCr front gate potential. The experiments were performed in a variable-temperature <sup>4</sup>He cryostat equipped with a superconducting magnet, employing a standard low-frequency lock-in technique for resistance measurement.

In Fig. 1 we show the normalized low-field magnetoresistivity  $\rho_{xx}(B)/\rho_{xx}(0)$  measured at  $T = 4$  K, for the electron density  $n_e = 2.05, 2.27$  and  $2.55$ , respectively. In addition to the damped SdH commonly seen in a 2DEG at this  $T$ , the traces reveal new oscillations that appear only at  $B < 0.3$  T. The amplitude of the oscillations is about 2–3% in these traces.



**Fig. 1.**  $\rho_{xx}(B)/\rho_{xx}(0)$  traces (shifted vertically for clarity) are shown for three densities  $n_e$  of  $2.05, 2.27$  and  $2.55 \times 10^{11}$  cm<sup>-2</sup>, respectively; arrows indicate the maxima for  $l = 1, 2, 3, 4$  and the shift of the primary ( $l = 1$ ) peak with increasing  $n_e$ ; Inset shows that the oscillations are periodic in  $1/B$ .

Three aspects of the observation should be highlighted. First, the oscillations are roughly periodic in inverse magnetic field,  $1/B$ . The arrows next to the traces indicate the  $\rho_{xx}(B_l)$  maxima (indexed as  $l = 1, 2, 3, 4$ ) in this oscillatory structure. In the inset we plot the order of the oscillations,  $l$  (and  $-d^2\rho_{xx}/dB^2$ ), vs.  $1/B$  for  $n_e = 2.55$  and observe a linear dependence. Such periodic oscillations have been seen for all  $n_e$  (from  $\sim 1.5$  to  $3$ ) studied. Second, with increasing  $n_e$  the features shift orderly towards the higher  $B$ . Finally, the

oscillatory structure is accompanied by a negative MR background, apparently in the same  $B$  range where the oscillations take place.

In the following we shall focus on the analysis of the oscillatory structure, in particular, their dependence on the  $n_e$  and  $T$ . To further quantify our results, we have performed fast Fourier transform (FFT) on the resistance data. Surprisingly, such analysis has uncovered two frequencies, marked by  $A$  and  $B$ . The peak  $A$  corresponds to the main period, conforming to a simple fit in Fig. 1. The peak  $B$  is somewhat weaker, and occurs at  $f_B \approx 1.5 f_A$ . The shift of the doublet with increasing  $n_e$  is marked by three arrows for the main peaks. The FFT data have revealed a striking linear relation between the frequencies of oscillations and the electron Fermi wave vector. We plot  $f^2$  of the FFT peaks against the electron density,  $n_e$ , which has been varied from 1.47 to 2.95 in the same specimen. Since  $k_F = \sqrt{2\pi n_e}$ , the observed linearity indicates that  $f \propto k_F$ .

Such a linear dependence distinguishes the new oscillations from SdH, as  $f_{\text{SdH}} \propto k_F^2$ , and is exactly what one expects from the phonon resonance scenario proposed here. As such, the oscillatory structure must be viewed as resulting from the resonance of the 2DEG with two branches of the interface modes. Using Eq. (1) and a single known material parameter, the GaAs band electron mass  $m \approx 0.068m_e$ , we fit the data (solid line in the inset) and deduce a velocity for the slow (fast) mode  $u_A \approx 2.9$  km/s ( $u_B \approx 4.4$  km/s). Within the experimental error of 10% the data from several specimen collapse on the same lines, indicating that new oscillations are generic in high-mobility 2DEG in GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures.

The  $T$ -dependence of the oscillations is consistent with a *thermally excited* phonon-scattering model. In our samples  $\rho_{xx}(0)$  grows linearly with  $T$ , indicating that acoustic-phonon scattering dominates the electron mobility in this temperature range [6, 7]. Considering the interface phonon modes of interest here, we rely on the value of the slow mode  $u_A = 2.9$  km/s to estimate a characteristic temperature,  $T_c$ , from  $k_B T_c = \hbar u_A (2k_F)$ . The value of  $T_c \approx 5$  K can qualitatively account for the temperature dependence of the main features of the oscillations. While the SdH gradually diminishes as  $T$  increases, the oscillations are best developed at  $T \approx 3-7$  K and are strongly damped at both higher and lower  $T$ . At  $T \ll T_c$  the number of interface phonons carrying  $q = 2k_F$  becomes small and therefore the amplitudes diminish. At high  $T$  the smearing of the LLs prevails and the oscillations disappear as well.

We now turn to the details of the theoretical explanation of the novel oscillations. We have performed the calculations [8] of LIP modes for the GaAs-Al<sub>0.3</sub>Ga<sub>0.7</sub>As interface on the basal (001) plane. In anisotropic case the speed of LIPs depends on an angle between  $q$  and the [100] direction. Using the elastic moduli of the bulk lattices[9] we found series of modes with weak anisotropy and a small imaginary part of the velocity ( $u_I/u_R < 0.03$ ). We have studied the modes within the interval of velocities 2.4–6.0 km/s. Two close groups of modes have been found within the interval of 3–3.5 km/s and that of 4.2–4.5 km/s, respectively. These modes may be responsible for two periods of oscillations which have been observed. The frequencies of the other modes found are too high to be detected in our experiment. Note that different modes may interact with electrons with a different strength.

To calculate the transverse conductivity due to the scattering of the 2DEG by the LIPs, we employ a 2D analog of the formula, first derived by Titeica.

$$\sigma_{xx} = \frac{4\pi e^2}{Am^2 k_B T \omega_c^2} \sum_{n,n'} \sum_{k_y,k'_y} \sum_{q_x,q_y} |I_{nn'}(q\lambda)|^2 q_y^2 |C(q)|^2 \times N_l f_n (1 - f_{n'}) \delta_{k_y - k'_y + q_y} \delta(\omega_c(n' - n) - qu). \quad (2)$$

Here  $A$  is the area,  $N_l = (\exp(\hbar\omega/k_B T) - 1)^{-1}$ ,  $f_n = (\exp((E_n - \mu)/k_B T) + 1)^{-1}$ ,  $\lambda = \sqrt{\hbar c/eB}$  is the magnetic length, and  $|C(q)|^2 \equiv v(q)/A$  is the square modulus of the 2DEG-LIP interaction, which has a power law dependence on  $q$ . This formula can be interpreted in the following way. A 2D electron in a magnetic field has a wave function which is a product of a plane wave in the  $y$  direction and an oscillatory wave function, centered at the position  $x_0 = -c\hbar k_y/eB$ :  $\Psi = \exp(ik_y y)\phi_n(x - x_0)$ , where  $n$  is the LL index. A transverse conductivity appears because an electron transfers wave vector  $q_y = k'_y - k_y$  to a scatterer. This is equivalent to a jump in the  $x$ -direction at a distance  $\Delta x_0 = c\hbar q_y/eB$ . In Eq. (2) this physics is applied to electron-interface phonon scattering.

The theory proves selection rule  $q = 2k_F$  and provides an interpretation of the rule.

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